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NAVAL AIR WARFARE CENTER AIRCRAFT DIVISION
PATUXENT RIVER, MARYLAND



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REPORT NO: NAWCADPAX/TR-2013/32

BIAXIAL FATIGUE CRACKING FROM NOTCH

by

**Eun U. Lee
Robert E. Taylor
Bruce A. Pregger
Charles Lei**

4 March 2013

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14. ABSTRACT A study was initiated to clarify the behavior of biaxial fatigue cracking from a notch, transverse or 45 deg inclined, in a cruciform specimen of a 7075-T651 aluminum alloy. The biaxial fatigue test was conducted in air and aqueous 3.5% NaCl solution at room temperature under in-phase and 180 deg out-of-phase loadings with biaxiality ratios, ranging from 0 to 1.5. Under in-phase loading, a greater biaxiality ratio extended the fatigue life and reduced the fatigue crack growth rate in both environments. On the other hand, under 180 deg out-of-phase loading, a greater biaxiality ratio shortened the fatigue life and increased the fatigue crack growth rate in both environments. Under the loadings of both phases, the fatigue growth life was shorter and the fatigue crack growth rate was greater in 3.5% NaCl solution than in air at a given biaxiality ratio. Such features evidence the acceleration of biaxial fatigue crack growth by 180 deg out-of-phase loading or/and by 3.5% NaCl solution. SEM fractographs of the biaxial fatigue crack surfaces showed ductile and brittle striations in the specimen fatigue-tested in air, and a mixture of both striations and intergranular cracking in the specimen fatigue-tested in 3.5% NaCl solution. Such fractographic features show the striation formation in air and a mixture of striation formation and intergranular cracking in 3.5% NaCl solution under biaxial fatigue loading. The biaxial fatigue crack growth rate, determined experimentally, was in partial agreement with that predicted by some reported models.					
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SUMMARY

Cruciform specimens were machined in T-L orientation from a 7075-T651 aluminum alloy sheet, and a notch, transverse or 45 deg inclined, was made at the center of each specimen. The specimens were subjected to cyclic biaxial loading, in-phase or 180 deg out-of-phase, at a fixed longitudinal stress of 49 MPa (7.11 ksi), biaxiality ratios, ranging from 0 to 1.5, stress ratio 0.1, and frequency 15 Hz, in air or aqueous 3.5% NaCl solution at room temperature. The growing crack length was measured, employing DC potential drop method, and the fatigue life and the fatigue crack growth rate were determined. It was observed that with increasing biaxiality ratio, the fatigue life was extended under in-phase loading but it was shortened under 180 deg out-of-phase loading. The fatigue life was also reduced by 3.5% NaCl solution under both loadings. The profile of fatigue crack path changed with biaxiality ratio under in-phase loading, but not under 180 deg out-of-phase loading. The fractographic features were ductile and brittle striations for the testing in air. They were a mixture of striations and intergranular cracking for the testing in 3.5% NaCl solution. The measured biaxial fatigue crack growth rate was compared with the prediction by reported models.

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NOMENCLATURE

a	half crack length
r	distance from the crack tip
E	Young's modulus
K_I, K_{II}	stress intensity factors
K_{max}	maximum stress intensity factor
ΔK	stress intensity range
N	number of cycle
$(N_{air})_{IP-I}$	fatigue life in air under in-phase loading for specimen with an inclined notch
$(N_{NaCl})_{IP-I}$	fatigue life in 3.5% NaCl solution under in-phase loading for specimen with an inclined notch
$(N_{air})_{OP-I}$	fatigue life in air under out-of-phase loading for specimen with an inclined notch
$(N_{NaCl})_{OP-I}$	fatigue life in 3.5% NaCl solution under out-of-phase loading for specimen with an inclined notch
$(N_{air})_{IP-T}$	fatigue life in air under in-phase loading for specimen with a transverse notch
$(N_{NaCl})_{IP-T}$	fatigue life in 3.5% NaCl solution under in-phase loading for specimen with a transverse notch
$(N_{air})_{OP-T}$	fatigue life in air under out-of-phase loading for specimen with a transverse notch
$(N_{NaCl})_{OP-T}$	fatigue life in 3.5% NaCl solution under out-of-phase loading for specimen with a transverse notch
R	stress ratio
Y	tensile yield stress of material
Z	normalized fatigue crack growth rate = $(da/dN)/(da/dN)_{\lambda=0}$
da/dN	fatigue crack growth rate
$(da/dN)_{\lambda=0}$	da/dN under uniaxial loading ($\lambda = 0$)
α	crack angle
θ	angle with respect to crack axis
κ	environment-dependent constant
λ	biaxiality ratio
σ	gross applied stress
σ_{max}	far field maximum stress in cycle
σ_u	ultimate tensile strength
$\sigma_y, \sigma_{xx}, \sigma_{yy}$	crack tip stresses
$\Delta\sigma$	stress range
τ_{xy}	shear stress in the vicinity of crack tip
ϕ	angle of loading phase

INTRODUCTION

It is recognized that in most working structures, including aircraft, the stress is not simple uniaxial. Biaxial or multiaxial stress situations usually exist. Thus, it is desirable to understand how a crack initiates and grows under complex stress situations, and in particular whether the biaxial stress state changes the crack initiation and growth processes. The crack initiation direction and its subsequent growth could be affected by applied stress biaxiality, loading phase and test environment.

It is also frequently found that fatigue cracks initiate and grow from notches, due to the effect of stress concentration. Therefore, fatigue crack growth from notches under a biaxial or multiaxial stress state has attracted increasing attention in recent years.

A notch or crack in a structure, subjected to biaxial or multiaxial loads, will typically not be aligned with either of the principal loading directions. Therefore, it is also important to understand the biaxial or multiaxial load effects on a specimen with an inclined notch or crack.

Crack propagation behavior under biaxial stress is dictated by three parameters: stress biaxiality, defined as the ratio of the in-plane principal stresses; notch or crack angle with respect to the applied principal stress direction; and stress intensity range. Depending on the first two parameters, cracks may grow in Mode I, Mode II, or Mixed-Mode.

Uniaxial fatigue crack growth has been studied extensively in air and corrosive environments. However, comparatively few studies have been reported for biaxial fatigue crack growth from a notch, transverse or inclined, in corrosive environment.

The crack path in an ideal homogeneous material is predictable for a given stress condition and angle of initial notch or crack. However, the actual path taken in a real sample, whether by unstable fracture or by fatigue crack growth, may deviate because of inhomogeneities. The inhomogeneities can be intrinsic to the original material, e.g., inclusions, and heat-treatment microstructures, or they can be induced by the presence of a growing crack, e.g., slip zones and sub-grains.

This study was initiated to clarify the effects of notch angle (transverse and 45 deg inclined), and stress biaxiality on the subsequent biaxial fatigue crack growth and life, under in-phase and 180 deg out-of-phase loading in air and 3.5% NaCl solution.

EXPERIMENTAL PROCEDURE

MATERIAL AND SPECIMEN

For the specimen material, a 2 mm (0.08 in.) thick sheet of aluminum alloy, 7075-T651, was selected. Its chemical composition and mechanical properties are shown in Tables 1 and 2, respectively.

Table 1: Chemical Composition of Aluminum Alloy 7075 (wt %)

Si	Fe	Cu	Mn	Mg	Cr	Zn	Ti	Other	Al
-0.50*	-0.7*	1.2-2.0	-3.0*	2.1-2.9	0.18-0.4	5.1-6.1	-0.20*	0.15	Balance

* maximum values

Table2: Mechanical Properties of Aluminum Alloy 7075-T651

YS (MPa)	UTS (MPa)	Elongation (%)
462	524	11

From the sheet, cruciform specimens were machined to have an overall length and width of 393 mm (15.5 in.), including the grip areas of the loading arms, Figure A-1. The vertical arms were in the transverse direction of the sheet and the horizontal ones in the longitudinal or rolling direction of the sheet. Each arm was 127 mm (5 in.) wide and 133 mm (5.2 in.) long. At the specimen center, a transverse or 45 deg inclined notch, 38 mm (1.5 in.) long and 0.25 mm (0.01 in.) wide, was made by electro-discharge machining. Subsequently, a precrack was made under cyclic biaxial loading until its length reached 1 mm (0.04 in.) from each end of the central notch.

BIAXIAL FATIGUE TEST

The biaxial fatigue test was conducted in a MTS 793.10 Multiaxial Purpose Test-Ware with two pairs of servo-hydraulic actuators and two pairs of load cells, arranged perpendicular to each other on a horizontal plane in a rigid frame, Figure A-1. This test machine was capable of static and cyclic biaxial loading in vertical and horizontal directions, separately or simultaneously. Tensile or compressive loads could be applied to each pair of the arms, developing a biaxial stress field in the working section. The cyclic biaxial loading, in-phase or 180 deg out-of-phase, was applied at a fixed longitudinal stress $\sigma_y = 49$ MPa (7.11 ksi), biaxiality ratios λ , ranging from 0 to 1.5, stress ratio $R = 0.1$ and loading frequency 15 Hz in air or aqueous 3.5% NaCl solution of pH 7.3 at room temperature. For the corrosion fatigue test, a pair of rectangular plastic cups was attached to the specimen, one cup on each side of the specimen, covering the notch and growing crack. During the test, the 3.5% NaCl solution was circulated between the cups and a reservoir by a pump. The growing crack length was measured by means of DC potential drop method. When the crack length reached 140 mm (5.51 in.), it was defined that the specimen was failed by fatigue.

FRACTOGRAPHY

The fatigue crack surface morphology was examined with a JEOL JSM-6460LV scanning electron microscope, operated at an accelerating voltage of 20 kV.

EXPERIMENTAL RESULTS

BIAXIAL FATIGUE CRACK GROWTH

Under in-phase loading, a greater biaxiality ratio λ extended the fatigue life N of a crack, growing from a notch, transverse or 45 deg inclined, and reduced the fatigue crack growth rate da/dN in both air and 3.5% NaCl solution, Figures A-2 and A-3. On the other hand, under 180 deg out-of-phase loading, a greater biaxiality ratio λ shortened the fatigue life N and increased the fatigue crack growth rate da/dN in the both environments, Figures A-4 and A-5.

Under in-phase and 180 deg out-of-phase loadings, the fatigue crack growth life was shorter and the fatigue crack growth rate was greater in 3.5% NaCl solution than in air at a given biaxiality ratio λ . Examples are shown for the crack growths from transverse and 45 deg inclined notches in Figures A-6 and A-7, respectively. These curves demonstrate the acceleration of biaxial fatigue crack growth in 3.5% NaCl solution.

The fatigue crack was found to grow faster under 180 deg out-of-phase loading than under in-phase loading at a given biaxiality ratio λ in air and 3.5% NaCl solution. Examples for the cracks, growing from transverse and 45 deg inclined notches, are shown in Figures A-8 and A-9, respectively. These curves demonstrate the acceleration of biaxial fatigue crack growth by 180 deg out-of-phase loading, compared to in-phase loading.

The variation of fatigue life with biaxiality ratio is shown in Figures A-10 and A-11 for the fatigue cracks, growing from transverse and 45 deg inclined notches, in air and 3.5% NaCl solution under in-phase and 180 deg out-of-phase loadings, respectively.

The empirical equations for the fatigue crack, growing from a transverse notch, under in-phase loading in the two environments are:

$$(N_{\text{air}})_{\text{IP-T}} = (3.26 + 6.19\lambda)10^5 \quad \text{Eq. (1)}$$

$$(N_{\text{NaCl}})_{\text{IP-T}} = (1.65 + 2.09\lambda)10^5 \quad \text{Eq. (2)}$$

From these equations and the two curves in Figure A-10(a), it is clear that the intercept and positive slope for the curve of fatigue life versus biaxiality ratio are greater in air than in 3.5% NaCl solution under in-phase loading.

For the fatigue crack, growing from a transverse notch, under 180 deg out-of-phase loading in air and 3.5% NaCl solution, the variation of fatigue life with biaxiality ratio is shown by two curves in Figure 10(b). The empirical equations for the two curves are:

$$(N_{\text{air}})_{\text{OP-T}} = (40.45 - 6.99\lambda)10^4 \quad \text{Eq. (3)}$$

$$(N_{\text{NaCl}})_{\text{OP-T}} = (17.10 - 2.80\lambda)10^4 \quad \text{Eq. (4)}$$

From these equations and the two curves in Figure 10(b), it is clear that the intercept and negative slope of the curve of fatigue life versus biaxiality ratio are greater in air than in 3.5% NaCl solution.

The empirical equations for the fatigue crack, growing from a 45 deg inclined notch, under in-phase loading in the two environments are:

$$(N_{\text{air}})_{\text{IP-I}} = (5.21 + 7.27\lambda)10^5 \quad \text{Eq. (5)}$$

$$(N_{\text{NaCl}})_{\text{IP-I}} = (2.31 + 3.04\lambda)10^5 \quad \text{Eq. (6)}$$

These equations and the two curves in Figure A-11(a) indicate that the intercept and positive slope of the curve of fatigue life versus biaxiality ratio are greater in air than in 3.5% NaCl solution.

The empirical equations for the fatigue crack, growing from a 45 deg inclined notch, under out-of-phase loading in the two environments are:

$$(N_{\text{air}})_{\text{OP-I}} = (5.37 - 1.30\lambda)10^5 \quad \text{Eq. (7)}$$

$$(N_{\text{NaCl}})_{\text{OP-I}} = (22.4 - 5.27\lambda)10^4 \quad \text{Eq. (8)}$$

These equations and the two curves in Figure A-11(b) also indicate that the intercept and negative slope of the curve of fatigue life versus biaxiality ratio are greater in air than in 3.5% NaCl solution.

In air and 3.5% NaCl solution, the biaxial fatigue life was observed to be longer under in-phase loading than under out-of-phase loading at a given biaxiality ratio λ for the crack, growing from a notch, transverse or 45 deg inclined. Furthermore, the difference becomes greater with increasing biaxiality ratio λ , as shown in Figures A-10(c) and (d), and A-11(c) and (d).

FATIGUE CRACK PATH

Under in-phase loading, the growth direction of a fatigue crack, propagating from a transverse notch, was found to be transverse at biaxiality ratio $\lambda = 0, 0.5$ and 1 , whereas it was 45 deg inclined at $\lambda = 1.5$, Figure A-12. Crack growth direction from a 45 deg inclined notch was transverse at $\lambda = 0$ and 0.5 , but 45 deg inclined at $\lambda = 1$, Figure A-13.

Under out-of-phase loading, the growth direction of a fatigue crack, propagating from a transverse or 45 deg inclined notch, was transverse at all biaxiality ratios employed, Figures A-12 and A-13.

These characteristic growth directions of biaxial fatigue cracks did not change with the change in environment, from air to 3.5% NaCl solution, under in-phase and out-of-phase loadings.

FRACTOGRAPHS

Two series of fractographs were selected to show the typical fractographic features. They were taken from two groups of specimens, one with transverse notches and the other with 45 deg inclined notches, fatigue-tested in air and 3.5% NaCl solution.

FRACTOGRAPHS OF THE SPECIMEN WITH A TRANSVERSE NOTCH

Figures A-14 through A-17 display equal magnification (X500) images of the crack surfaces at 1.5, 2.5, 3.5, and 4.5 cm from the notch tip for the specimens tested in air and 3.5% NaCl solution, respectively. The crack surface of the specimen tested in air consists of parallel grain facets, elongated in the initial sheet rolling direction. Most of those facets exhibit coarse ductile striations and irregular brittle striations, some appear smooth without resolved features, and a few dimples are noticeable around inclusions. On the other hand, the crack surfaces of the specimens tested in 3.5% NaCl solution show intergranularly separated elongated grains with ductile and brittle striations, dimples, and some corrosion products. More dimples are visible in the both environments and less corrosion products in 3.5% NaCl solution at a spot farther from the notch tip on the crack surface.

Figures A-18 and A-19 show higher magnification (X1000) images of the crack surfaces at 3.5 and 4.5 cm from the notch tip, respectively. Fine, well formed ductile striations were visible on the smooth grain facets of the specimens tested in air. For the specimens tested in 3.5% NaCl solution, on the other hand, the ductile striations appear poorly defined and coarser with wider spacing.

FRACTOGRAPHS OF THE SPECIMEN WITH A 45 DEG INCLINED NOTCH

Figures A-20 through A-25 show images of the crack surfaces at 0.03, 0.3, 1.4, 2.5, 3.5, and 4.5 cm from the notch tip, respectively. The common features of the fractographs of the specimens tested in air are parallel elongated grains containing ductile and brittle striations, and dimples around inclusions. Features seen on the specimens tested in 3.5% NaCl solution are intergranularly separated elongated grains with ductile and brittle striations, dimples, and corrosion products. Nearer the notch tip, the corrosion products contain mud-cracks and obscure the crack surface more, as shown in Figure A-20.

Figures A-26, A-27, and A-28 show higher magnification (X3500) images of the crack surfaces at 2.5 and 4.3 cm from the precrack-tips. Well-defined ductile striations are visible in the specimens tested in air, whereas the ductile striations seen in the specimens tested in 3.5% NaCl solution are poorly defined and relatively coarse (red arrow).

DISCUSSION

BIAXIALITY AND STRESS STATE

The theoretical treatment of biaxial stress can be based on the Williams' elastic equations for the stress state around a crack tip (reference 1). The state of plane elastic stress in the neighborhood of a crack tip, Figure A-29, is expressed as:

$$\sigma_{yy} = (K_I/\sqrt{2\pi r})\{\cos(\theta/2)\}\{1 + \sin(\theta/2)\sin(3\theta/2)\} + (K_{II}/\sqrt{2\pi r})\{\sin(\theta/2)\cos(\theta/2)\cos(3\theta/2)\} \quad \text{Eq. (9)}$$

$$\sigma_{xx} = (K_I/\sqrt{2\pi r})\{\cos(\theta/2)\}\{1 - \sin(\theta/2)\sin(3\theta/2)\} - (K_{II}/\sqrt{2\pi r})\{\sin(\theta/2)\}\{2 + \cos(\theta/2)\cos(3\theta/2)\} + (1 - \lambda)\sigma\cos(2\alpha) \quad \text{Eq. (10)}$$

$$\tau_{xy} = (K_I/\sqrt{2\pi r})\{\sin(\theta/2)\cos(\theta/2)\cos(3\theta/2)\} + (K_{II}/\sqrt{2\pi r})\{\cos(\theta/2)\}\{1 - \sin(\theta/2)\sin(3\theta/2)\} \quad \text{Eq. (11)}$$

where

$$K_I = \{(\sigma\sqrt{\pi a})/2\}\{(1 + \lambda) - (1 - \lambda)\cos(2\alpha)\} \quad \text{Eq. (12)}$$

$$K_{II} = \{(\sigma\sqrt{\pi a})/2\}\{(1 - \lambda)\sin(2\alpha)\} \quad \text{Eq. (13)}$$

Equations (9) through (13) show that one of the stress components σ_{xx} , and stress intensity factors K_I and K_{II} are affected by the biaxiality ratio λ . There are three distinct situations which arise from the generalized case:

- (a) Mode I growth, where the crack is aligned normal to either principal stress or $\alpha = \pi/2$
 - $K_{II} = 0$ for any λ value.
 - K_I and σ_{yy} are not affected by λ , but the transverse stress σ_{xx} is directly related.
- (b) Mode II growth where the crack is aligned along the maximum shear stress direction i.e., $\alpha = \pi/4$ and $\lambda = -1$
 - $K_I = 0$
- (c) Mixed-Mode growth where $\alpha \neq \pi/2$ or $\alpha \neq 0$
 - λ may be any value.

EFFECT OF BIAXIALITY RATIO ON FATIGUE CRACK GROWTH

The biaxial fatigue crack growth under in-phase loading was also subjected to analytical study by some investigators (references 2 and 3). Ahmad (reference 2) derived the following equation.

$$da/dN = (da/dN)_{\lambda=0} [\text{reference } 1 + \{(\lambda\sigma_{\max})/(Y - \sigma_{\max})\}]^{-1} \quad \text{Eq. (14)}$$

This equation indicates that a greater λ induces a smaller da/dN . This agrees with the experimental results of this study for all cases of in-phase loadings: the fatigue crack growth

from a notch, transverse or 45 deg inclined, under in-phase loading in air and 3.5% NaCl solution, as shown in Figures A-2 and A-3.

The normalized fatigue crack growth rate, $Z = (da/dN)/(da/dN)_{\lambda=0}$, calculated with the values of λ , σ_{\max} and Y of the test and its material (7075-T651 aluminum alloy), and employing the above Ahmad's equation (reference 14), is compared with the test value in Figure A-30(a). This figure shows that Z or da/dN varies with λ and stress intensity range ΔK . It also indicates that there is a significant difference between the prediction by Ahmad's model and the test value; this difference becomes larger with greater λ . Ahmad's model predicts the change in the normalized fatigue crack growth rate ΔZ with λ to be much smaller than that observed experimentally, as shown in the following table.

	ΔZ between $\lambda = 0$ and 1.5
Model	0.16
$\Delta K = 5.0$	0.60
$\Delta K = 6.0$	0.75

Brown (reference 3) reported the following equation for the biaxial fatigue crack growth.

$$da/dN = 18(\sigma_u/E)^2 a (\pi^2/2) [\lambda - 1 + \{16(\sigma_u/\Delta\sigma)^2 - 3(\lambda - 1)^2\}^{1/2}]^{-2} \quad \text{Eq. (15)}$$

This equation indicates that the biaxial fatigue crack growth is accelerated by greater ultimate tensile strength σ_u and crack length a , but decelerated by greater biaxiality ratio λ . This is in agreement with the test result of this study, shown in Figures A-2 and A-3. The value of da/dN calculated with the above equation (15) is compared with the test value in Figure A-30(b). The value of the Brown's model (reference 3) is greater than the test value, the difference increasing at higher biaxiality ratio.

A number of investigators (references 4 and 5-8) reported the extension of fatigue life N and reduction of fatigue crack growth rate da/dN with increasing biaxiality ratio λ , which are in agreement with the observations made in this study. Hopper (reference 4) reported that da/dN and crack tip plastic zone size are greatest for $\lambda = -1$, intermediate for $\lambda = 0$ and smallest for $\lambda = 1$ in RR58 aluminum alloy. On the basis of the semi-empirical expressions derived, Jones (reference 5) predicted that an increase in tensile load biaxiality should reduce the da/dN relative to that for uniaxially cycled load. This prediction was confirmed by his experimental work with 2024-T3 and 7075-T6 aluminum alloys for the biaxiality ratios, ranging from 0 to 1.5. Hoshide (reference 6) observed that the da/dN was higher in the order of $\lambda = 0, 1, -1$ for the stress ratio $R = 0$, and in the order of $\lambda = -1, 0, 1$ for $R = -1$ in a structural low-carbon steel (JIS SM41C). After studying the reduction of plastic zone size and crack opening displacement, Adams (reference 9) made a theoretical prediction of da/dN reduction with increasing λ . Miller (reference 10) found smaller da/dN for a greater λ , and decreasing crack tip plastic zone size with decreasing da/dN and increasing λ in RR58 aluminum alloy. Leever (reference 11) noticed that the variation in λ from 0 to 2 has little effect on the da/dN in PVC (polyvinyl-chloride), but reduces the da/dN in PMMA (polymethyl methacrylate). Kitagawa (reference 12) found decreasing da/dN with

increasing load amplitude parallel to a crack during the biaxial testing of a weldable structural steel.

EFFECT OF ENVIRONMENT ON FATIGUE CRACK GROWTH

Yunki (reference 13) conducted corrosion fatigue tests of a high tensile strength steel (WT60) and a stainless steel (SUS304) in a 3.5% NaCl solution under in-phase biaxial stress conditions. The results showed that the fatigue crack growth was accelerated by corrosive environment as in a uniaxial test; the acceleration was more significant at a lower stress intensity range ΔK . This is mostly in agreement with the finding in this study, as shown in Figures A-6 and A-7. Wahab (reference 14) found the fatigue life of a welded mild steel (C1020) structure reduced by corrosive environment, 3.5% NaCl solution, under biaxial rotating and bending.

Ahmad (reference 2) formulated a model for the biaxial fatigue crack growth in aggressive environment, outlined by the following equation.

$$da/dN = 0.077(\kappa/EY)(1 - 0.2R - 0.8R^2)K_{\max}^2[1 - (1 - \lambda)(\sigma_{\max}/Y)]^{-1} \quad \text{Eq. (16)}$$

According to Ahmad, the environment-dependent constant κ is small compared to unity in a benign environment, while it approaches unity in an aggressive environment. The variation of κ with λ was found by substituting the values of E and Y of the test material, 7075-T651 aluminum alloy, and the values of the employed test parameters in the above equation (16), as shown in Figure A-31. The value of κ is greater in 3.5% NaCl solution than in air, and decreases with increasing λ . It ranges from 0.12 to 0.05 in air and from 5.73 to 0.15 in 3.5% NaCl solution for λ increasing from 0 to 1.5. This test result is in partial agreement with Ahmad's model prediction (reference 2).

EFFECT OF OUT-OF-PHASE LOADING ON FATIGUE CRACK GROWTH RATE

The fatigue life has been found to be dependent upon whether there is a phase difference in the variation of biaxial stress. After analyzing the opening and closing behavior of fatigue crack under biaxial loading, Ogura (reference 15) concluded that the fatigue crack growth is accelerated by out-of-phase biaxial stress while it is little affected by in-phase stress. Miller (reference 16) analyzed the shear and normal stresses for an out-of-phase condition, and suggested the following. When the phase angle ϕ is 60 deg for sinusoidal loading or 90 deg for triangular loading, two different crack growth systems interfere with one another and the fatigue life is extended. However, at ϕ values greater than this unique angle, one of the crack growth systems dominates and the fatigue life decreases. This is in agreement with the finding in this study: the biaxial fatigue life decreased at $\phi = 180$ deg. Kanazawa (reference 17) conducted biaxial fatigue tests on a Cr-Mo-V steel tube under cyclic axial and torsional loads with various phase relations, and showed that the fatigue life shortened with out-of-phase loading. Kitagawa (reference 12) noticed da/dN increasing with changing phase difference from 0 to π at $\lambda = 1$ during a biaxial fatigue test of weldable structural steel. McDiarmid (reference 18) carried out a series of biaxial fatigue tests on thin-wall tubular specimens of EN24T steel, and observed that the biaxial fatigue life was shorter for $\phi = 180$ deg than for $\phi = 0$ deg at $\lambda = 1$ and a given frequency. This observation is in agreement with the result of this study.

FRACTOGRAPHY OF FATIGUE CRACK GROWTH

STRIATIONS

Two types of fatigue striation, referred to as ductile and brittle striations, have been classified (reference 19). Ductile striations are the type commonly observed on uniaxial fatigue cracks in air, while brittle ones have been observed on uniaxial corrosion fatigue cracks and in hydrogen-embrittled steels (reference 19). However, in this study, brittle striations were observed not only in 3.5% NaCl solution but also in air under biaxial fatigue loading, Figures A-14 through A-25.

Brittle striations have been reported to form on crystallographic crack planes in aluminum alloys fatigue-loaded uniaxially in air and corrosive environment (reference 20). Their roughness is the result of the crystallographic mode of cracking or fracture. Within each grain, the fracture path associated with corrosion fatigue looks like a cleavage plane. Because of the difference in orientation from grain to grain, a part of the crack front propagates in a ductile manner and the other in a brittle manner, creating patches or facets of ductile and brittle striations.

In this study, the fatigue striation spacing, a measure of fatigue crack growth rate da/dN , was observed to be wider on the specimen tested in 3.5% NaCl solution than on the specimen tested in air, Figures A-26 and A-28. This observation confirms the acceleration of crack growth under biaxial corrosion fatigue conditions, Figures A-6 and A-7.

INTERGRANULAR CRACKING

In this study, intergranular cracking of 7075-T651 aluminum alloy was observable under biaxial fatigue loading in 3.5% NaCl solution, Figures A-14 through A-19 and A-21 through A-25.

Intergranular cracking was previously been reported occurring in a solution-treated and peak-aged Al-5.6Zn-1.0Mg sample, which was subjected to uniaxial corrosion fatigue loading in high-purity deaerated water and 0.5 mol NaCl solution (reference 20).

Intergranular cracking or fracture is usually attributable to segregation of thermally activated impurities, which allows the grains to separate along interfacial planes. Such cracking or fracture occurs during hydrogen embrittlement, stress corrosion cracking or corrosion fatigue under uniaxial loading (reference 21). Depending on the environment and exposure period, the crack surface may display greater or lesser amounts of corrosion products.

DIMPLE

In this study, the fatigue crack growth was observed to be accompanied by dimple formation around inclusions at high rates of crack growth, Figures A-14 through A-25.

Similar dimple formation was reported previously under uniaxial fatigue loading. Lee et al, found more and larger dimples in 4340, 300M, AerMet 100 and 13-8Mo steels at greater fatigue crack growth rates in vacuum, air and 3.5% NaCl solution (reference 22).

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CONCLUSIONS

1. The biaxial fatigue crack growth is accelerated by 3.5% NaCl solution and 180 deg out-of-phase loading.
2. The biaxial fatigue life is extended and the fatigue crack growth rate is reduced by increasing biaxiality ratio under in-phase loading, confirming the theoretical prediction. However, the opposite behavior is observed under out-of-phase loading.
3. The biaxial fatigue crack path profile changes with biaxiality ratio under in-phase loading, but does not under 180 deg out-of-phase loading in the specimen with a transverse or 45 deg inclined notch. Furthermore, it does not change with the change in test environment, from air to 3.5% NaCl solution.
4. The fractographic features are ductile and brittle fatigue striations for the test in air, and a mixture of striations and intergranular cracking for the test in 3.5% NaCl solution. The striation spacing is wider under corrosion fatigue condition, confirming the acceleration of fatigue crack growth in 3.5% NaCl solution.

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APPENDIX A
FIGURES

1. MTS Machine and Cruciform Specimen
2. Effect of Biaxiality Ratio on Fatigue Life and Crack Growth Rate in Air and 3.5% NaCl Solution under In-Phase Loading for Specimen with Transverse Notch
3. Effect of Biaxiality Ratio on Fatigue Life and Crack Growth Rate in Air and 3.5% NaCl Solution under In-Phase Loading for Specimen with 45 deg Inclined Notch
4. Effect of Biaxiality Ratio on Fatigue Life and Crack Growth Rate in Air and 3.5% NaCl Solution under Out-of-Phase Loading for Specimen with Transverse Notch
5. Effect of Biaxiality Ratio on Fatigue Life and Crack Growth Rate in Air and 3.5% NaCl Solution under Out-of-Phase Loading for Specimen with 45 deg Inclined Notch
6. Effect of Environment on Fatigue Life and Crack Growth Rate under In-Phase and Out-of-Phase Loading of Biaxiality Ratio 1 for Specimen with Transverse Notch
7. Effect of Environment on Fatigue Life and Crack Growth Rate under In-Phase and Out-of-Phase Loading of Biaxiality Ratio 1 for Specimen with 45 deg Inclined Notch
8. Effect of Loading Phase on Fatigue Life and Crack Growth Rate at Biaxiality Ratio 1 in Air and 3.5% NaCl Solution for Specimen with Transverse Notch
9. Effect of Loading Phase on Fatigue Life and Crack Growth Rate at Biaxiality Ratio 1 in Air and 3.5% NaCl Solution for Specimen with 45 deg Inclined Notch
10. Variation of Fatigue Life with Biaxiality Ratio under In-Phase and 180 deg Out-of-Phase Loading in Air and 3.5% NaCl Solution for Specimen with Transverse Notch
11. Variation of Fatigue Life with Biaxiality Ratio under In-Phase and 180 deg Out-of-Phase Loading in Air and 3.5% NaCl Solution for Specimen with 45 deg Inclined Notch
12. Profiles of Fatigue Crack Path under In-Phase and 180 deg Out-of-Phase Loadings of Various Biaxiality Ratios in Air and 3.5% NaCl Solution for Specimen with Transverse Notch
13. Profile of Fatigue Crack Path under In-phase and 180 deg Out-of-Phase Loadings of Various Biaxiality Ratios in Air and 3.5% NaCl Solution for Specimen with 45 deg Inclined Notch
14. SEM Fractographs at 1.5 cm from Transverse Notch Tip

15. SEM Fractographs at 2.5 cm from Transverse Notch Tip
16. SEM Fractographs at 3.5 cm from Transverse Notch Tip
17. SEM Fractographs at 4.5 cm from Transverse Notch Tip
18. SEM Fractographs at 3.5 cm from Transverse Notch Tip
19. SEM Fractographs at 4.5 cm from Transverse Notch Tip
20. SEM Fractographs at 0.03 cm from 45 deg Inclined Notch Tip
21. SEM Fractographs at 0.3 cm from 45 deg Inclined Notch Tip
22. SEM Fractographs at 1.4 cm from 45 deg Inclined Notch Tip
23. SEM Fractographs at 2.5 cm from 45 deg Inclined Notch Tip
24. SEM Fractographs at 3.5 cm from 45 deg Inclined Notch Tip
25. SEM Fractographs at 4.3 cm from 45 deg Inclined Notch Tip
26. SEM Fractographs at 2.5 cm from 45 deg Inclined Notch Tip
27. SEM Fractographs at 2.5 cm from 45 deg Inclined Notch Tip
28. SEM Fractographs at 4.3 cm from 45 deg Inclined Notch Tip
29. Crack Situation for Applied In-Plane Biaxial Stress
30. Variation of Fatigue Crack Growth Rate with Biaxiality Ratio, Determined Experimentally and Employing Reported Models
31. Variation of Ahmad's Environment-Dependent Constant κ with Biaxiality Ratio in Air and 3.5% NaCl Solution (reference 11)

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